(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) **EP 2 200 096 A1**

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
23.06.2010 Bulletin 2010/25

(51) Int Cl.:
H01L 31/107 *(2006.01)* *H01L 31/0304* *(2006.01)*

(21) Application number: **08305969.1**

(22) Date of filing: **18.12.2008**

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MT NL NO PL PT RO SE SI SK TR
Designated Extension States:
AL BA MK RS

(71) Applicants:
- **Alcatel Lucent**
  75008 Paris (FR)
- **Thales**
  92200 Neuilly-sur-Seine (FR)

(72) Inventor: **Achouche, Mohand**
91460, Marcoussis (FR)

(74) Representative: **Shamsaei Far, Hassan**
Alcatel Lucent
Intellectual Property & Standards
54 rue La Boétie
75008 Paris (FR)

(54) **Avalanche photodiode**

(57) A single carrier avalanche photodiode (200) comprising a p-doped absorption layer (213), an unintentionally doped avalanche multiplication layer (203) and an n-doped collector layer (211) and a method of manufacturing said avalanche photodiode. The absorption layer is doped at a level that allows the photodiode to operate as a single carrier device. Therefore total delay time of the device is mainly dependent on electrons. The collector layer (211) is in charge of reducing capacitance in the device. A built-in field layer (212) of n+ δ doped material may be provided between the two layers in order to improve the injection of electrons in the collector layer.

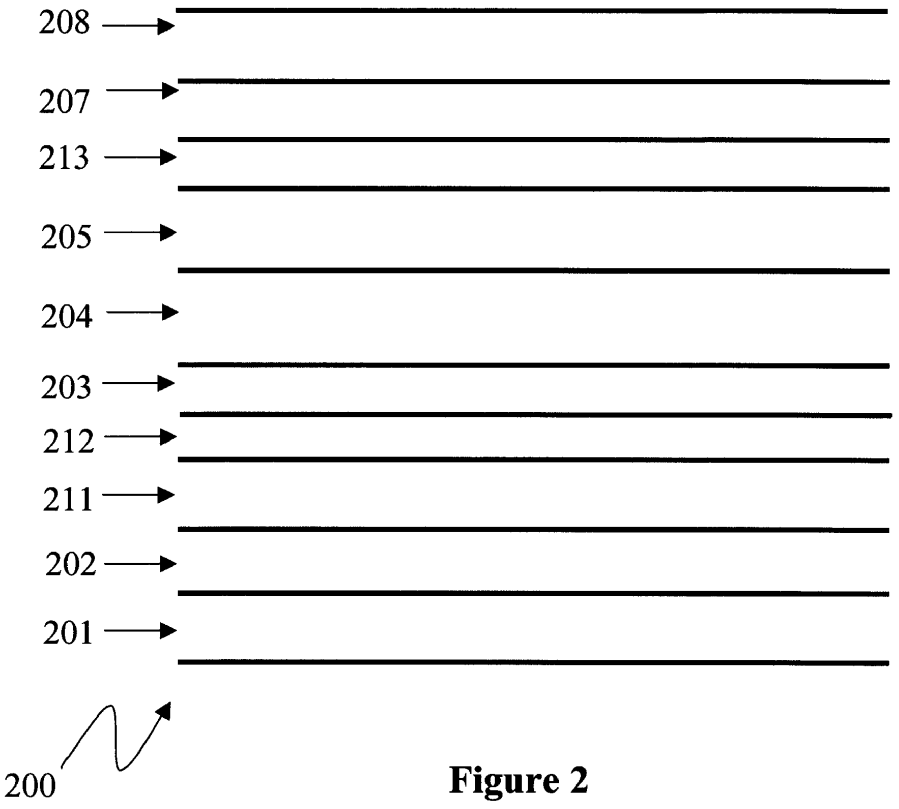


Figure 2

EP 2 200 096 A1

Description

[0001] The present invention relates to avalanche photodiodes.

BACKGROUND ART

[0002] Avalanche photodiodes (APD) are widely used as components for many applications in telecommunication such as fiber optics transmission systems, free-space optics communication, as well as for other optical applications such as height resolution, ranging, sensing, spectroscopy and the like, due to the fact that their internal gain improves considerably the sensitivity of photoreceivers for the particular application. Currently, APDs are used for increasing the power budget for channel data rates below 10 Gb/s. However, it is considered to be very likely that similar paths are followed with the deployment of high speed networks with data rates at or above 10 Gb/s, which presently operate using pin receivers. Indeed the expected significant improvement in sensitivity, expected to reach as far as about 10 dB, may allow for replacing expensive gain block units such as erbium-doped fiber amplifiers (EDFAs) by APDs; or in some case, for example at a rate of about 40 Gb/s, to introduce new optical processing elements such as dispersion compensating modules in 40 Gb/s transponders.

[0003] For high bit rate applications such as 40 Gb/s, some important issues to be taken into consideration in order to achieve high sensitivity avalanche photodiodes are a high level of responsivity, a wide bandwidth at low multiplication gain and an optimum gain-bandwidth product.

[0004] In order to achieve such objectives, one known solution employed in the recent years is the use of lateral-illumination for APDs because it allows for reducing the thickness of the absorption layer so as to reduce transit time without compromising the responsivity. This leads to improved bandwidth at low gains compared to conventional surface-illuminated APDs. However, this type of APDs also suffer from limitations in design in order to achieve wide bandwidth at low multiplication gains and high gain-bandwidth product.

[0005] One such limitation is related to device size. While these devices allow for further reduction of device active area in order to improve limitation in bandwidth caused by the RC filtering effect in the device (in general, the bandwidth depends on photogenerated carriers transit time and RC-low pass filter), such reduction of device size however degrades device responsivity due to a corresponding reduction of the absorption area and volume.

[0006] Another limitation of such devices is related to the gain-bandwidth product. In principle, it should be possible to improve the gain-bandwidth product by reducing the thickness of the multiplication layer (including the thickness of the transition layer). However, an excessively thin transition layer (composed of a grading layer and a charge layer) gives rise to the production of unwanted multiplication in the absorption region.

[0007] On the other hand, in order to achieve high multiplication gains, a thick avalanche layer is needed so as to support an electric field which is sufficiently high in order to produce high ionization of photogenerated carriers (carriers acquiring high energy) without excessive dark current.

SUMMARY OF THE INVENTION

[0008] Embodiments of invention feature a single carrier avalanche photodiode comprising a p-doped absorption layer, an unintentionally doped avalanche multiplication layer and an n-doped collector layer, the collector layer being capable of collecting electrons injected from the avalanche layer.

[0009] According to some embodiments of the invention the avalanche photodiode comprises, a built-in filed layer of n+ doped material provided between the avalanche multiplication layer and the collection layer.

[0010] According to some embodiments of the invention, the p-doped absorption layer is doped at about $5x10^{17}$ cm^{-3} or comprises a gradual p-doping level which varies between $5x10^{17}$ cm^{-3} and $2x10^{18}$ cm^{-3}.

[0011] According to some embodiments of the invention, the p-doped absorption layer is of InGaAs material or GaAsSb material.

[0012] According to some embodiments of the invention, the collector layer is of GaInAsP material.

[0013] According to some embodiments of the invention, the built-in field layer is of InAlAs material.

[0014] Further embodiments of the invention feature a method of manufacturing an avalanche photodiode comprising the steps of:

- generating a p-doped absorption layer,
- generating an unintentionally doped avalanche multiplication layer; and
- generating an n-doped collector layer, the collector layer being capable of collecting electrons injected from the avalanche layer.

[0015] According to some embodiments of the invention, the method further comprises the step of generating a built-in filed layer of n+ doped material between the avalanche multiplication layer and the collection layer.

[0016] According to some embodiments of the invention, the step of generating a p-doped absorption layer comprises a doping of said absorption layer at about $5x10^{17}$ cm^{-3} or comprises a gradual p-doping level which varies between $5x10^{17}$ cm^{-3} and $2x10^{18}$ cm^{-3}.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]

Figure 1 is a schematic representation of a structure of a conventional avalanche photodiode.

Figure 2 is a schematic representation of a structure of an avalanche photodiode according to embodiments of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0018] For a better understanding of the structure of the APD proposed herein, reference is first made to some known structures of APDs.

[0019] A first example is an APD structure comprising an avalanche layer made of a bulk AlInAs material or an AlInAs/AlGaInAs MQW (Multiple Quantum Well) and an absorption layer of GaInAs material. The bulk multiplication layer is made thin enough so as to allow for a large ionization coefficient ratio k by reduced fluctuation in multiplication events, where k= α/β, α and β being the ionization coefficients of electrons and holes respectively. This results in reducing excess noise and enhances gain-bandwidth product. Using a waveguide for lateral-illumination and very thin absorption (about 0.5 μm) and multiplication (about 0.1 μm) layers, an APD has demonstrated a 3-dB bandwidth of 30 GHz at low gains and a limited gain-bandwidth product of 140 GHz. This is not a satisfactory result because for high speed operations at 40Gb/s, this low gain-bandwidth product limits the avalanche gain to M=3-4 which is not desirable.

[0020] It is further to be noted that both figures 1 and 2 represent only schematic and simplified illustrations of layers of avalanche photodiode structures. These figures are therefore not in scale.

[0021] Reference is now made to figure 1 with the aim of briefly describing the structure of a conventional APD in which only those elements which are relevant for the present discussion are represented.

[0022] Figure 1 schematically represents a structure of a conventional APD 100 comprising a substrate 101 typically of InP, an N contact layer 102 typically of N-doped material, the material being for example InAlAs, an avalanche layer 103 typically of undoped InAlAs material, a charge layer 104 typically of P-doped InAlAs material, a grading layer 105 of unintentionally doped InGaAlAs material, an absorption layer 106 of undoped InGaAs material, a window layer 107 of P-doped InP material and a P contact layer 108 of InGaAs material. It is to be noted that the above materials are only provided in an exemplary manner and those skilled in the art realize that other materials are also usable in the construction of a conventional APD.

[0023] The characteristics of the above mentioned layers are generally known to a person skilled in the related art. In brief, an absorption layer is capable of absorbing photons from an incident light so as to generate electron/hole pairs which travel into the avalanche multiplication layer. In the avalanche multiplication layer the electrons and holes are multiplied by the avalanche effect. The grading layer provides a smooth transition of the generated carriers from the absorption layer to the avalanche multiplication layer. The charge layer contributes in providing a high electric field in the avalanche multiplication layer while the electric filed in the absorption layer is maintained a low in order to avoid tunneling effect. The P and N contact layers provide contacting possibility with the bias voltage which is intended to be applied on the device structure in order to provide the required electric field.

[0024] The layers are formed according to known methods such as for example epitaxial growth.

[0025] Figure 2 schematically represents a structure of an APD 200 according to some embodiments of the present inventions. The APD 200 structure comprises a substrate 201 of InP, an N contact layer 202 of N-doped material for example GaInAsP (InAlAs may also be used as an alternative material, however GaInAsP is preferred because the collector layer uses a similar material, GaInAsP), an avalanche layer 203 of undoped InAlAs material, a charge layer 204 of P-doped InAlAs material, a grading layer 205 of unintentionally doped InGaAlAs material, an absorption layer 213 as will be described in further detail below, a window layer 207 of P-doped InP material and a P contact layer 208 of p-doped InGaAs material. It is to be noted that the above materials are only provided in an exemplary manner and those skilled in the art realize that other materials are also usable in the construction of a conventional APD.

[0026] According to embodiments of the invention, the APD further comprises at least two drift regions (instead of one in conventional APDs). A first region, similar to conventional APDs, is the avalanche multiplication layer 203. This level however is preferably unintentionally doped AlInAs that provides internal gain in the photodiode by impact ionization process. A second region is a collector layer 211 which is in charge of reducing capacitance in the device. The collector layer 211 is preferably of n- doped (Ga)In(As)P material which collects injected electrons from the avalanche layer. The doping level of the n-doped collector layer is preferably in the order of about $1x10^{16}cm^{-3}$ and having a preferred thickness of about 0.2μm.

[0027] Preferably, a built-in field layer 212 of n+ doped material is provided between avalanche multiplication layer 203 and the collector layer 211 in order to improve the injection of electrons in the collector layer 211. The built-in field layer 212 is preferably made very thin, namely of a thickness in the order of about 0.03μm to about 0.07 μm, and preferably about 0.05μm. The n+ doped material of the built-in field is preferably AlInAs being highly doped, namely in order of about $7x10^{18}cm^{-3}$ or higher.

[0028] In addition according to embodiments of the present invention, the light absorption layer 213 of the APD 200 is slightly p-doped (as opposed to the undoped absorption layer comprised in a conventional APD 100). The p-doped light absorption layer 213 is for example of GaInAs material, being doped at a level of about $5x10^{17}$ cm^{-3} or comprises a gradual p-doping level which varies between $5x10^{17}$ cm^{-3} and $2x10^{18}$ cm^{-3}.

[0029] Alternatively, the p-doped absorption layer may be of GaAsSb material typically used for detection of a 1.55μm wavelength, the level of doping being approximately similar to the GaInAs material.

[0030] The fact that the absorption layer 213 is doped at such levels allows the photodiode to operate as a single carrier device. This is because when the APD is biased the photogenerated majority holes inside the absorption layer 213 diffuse to the p-contact layer 208 and thus have a relatively fast response within the dielectric relaxation time. The P contact layer 208 acts as a diffusion block layer because of the existence of a wide bandgap and the voltage applied, thereby forcing the diffusion of electrons toward the avalanche layer 203 where they experience the avalanche multiplication under the electric field applied to the device. As a consequence, the device operates substantially as a single carrier device that uses substantially only electrons as active carriers. Therefore total delay time of the device is related to (or dependent on) only electrons because secondary holes generated by impact ionization process are collected in the adjacent absorption layer (which is slightly p-doped).

[0031] With the use of a single carrier avalanche photodiode substantially only photo-excited electrons are used as active carriers in the pin-structure.

[0032] As mentioned above, the p-contact layer 208 acts as a diffusion block layer that causes a unidirectional motion in the electrons so as to move them toward the avalanche multiplication layer 203, thus contributing to a pure electron injection avalanche structure thereby improving noise and gain-bandwidth product. This is due to reduced delay time and single carrier type injection which is, as is known, contributes to improve both noise figure and gain-bandwidth product.

[0033] Secondary holes which may be generated by the avalanche multiplication process would present a reduced transit time compared to secondary holes produced in conventional APD structures, because in the new APD structure according to the invention these holes are not caused to drift inside the p-doped absorption layer 213 as they are majority carriers in the latter layer.

[0034] On the other hand, the presence of a collector layer 211 between the avalanche layer 203 and the n-doped contact layer 202 in the single carrier APD proposed herein, contributes to an efficient transfer of electrons to the n-doped contact layer 202 and reduces the capacitance in the device thus improving (reducing) the RC effect bandwidth limitation and consequently improving the photodiode gain-bandwidth product.

[0035] Based on the structure proposed by embodiments of the invention, the absorption layer may be formed at a thickness which is comparatively lower (for example about 0.18 μm) as compared to a thickness typically formed for an absorption layer in conventional APDs (for example 0.3 μm). This reduction contributes to reducing the transit time and to improve bandwidth.

[0036] The new solution provides improved bandwidth at low multiplication gains and higher gain-bandwidth product owing to the single carrier operation of the device structure: the electron velocity at overshoot is larger than the holes saturation velocity (about one order of magnitude). Herein, overshoot is understood to correspond to a transitory regime where carriers achieve a velocity that is higher than the equilibrium velocity or saturation velocity.

[0037] Using the conventional APD structure represented in figure 1, and for a given device area, in order to achieve wide bandwidth at low multiplication gains and high gain-bandwidth product, it is necessary to reduce carriers transit time using thin absorption layer 106 and thin avalanche multiplication active layer 103. However, if the thickness of the avalanche multiplication layer 103 is reduced to values below 0.1 μm, the maximum available gain will become degraded due to a combination of a reduced breakdown voltage (because a large electric field may not be reached as needed for impact ionization process) and high dark current due to carriers tunneling effect under high applied bias voltage (for the sake of clarity it is to be noted that the electric field in the absorption layer is kept low while it is large enough in the avalanche layer to generate carriers by impact ionization mechanism). Also, an AlInAs avalanche layer is usually chosen thin enough to improve the noise figure of the device, however this is achieved at the expense of generating a high capacitance in the device.

[0038] As regards transit time and multiplication gain characteristics with respect to a specific absorption layer thickness, for example 200 nm, experiments have shown that for a conventional APD 100 as described in relation to figure 1, the transit time may vary from values of about 9 ps for a multiplication gain of 1, to about 16.6 ps for a multiplication gain of 10.

[0039] In contrast, using a single carrier APD 200 as proposed herein (and described with reference to figure 2), it is observed by experimentation that for an absorption layer thickness of 200 nm, the transit time is improved by a factor of about 2 in comparison to a conventional APD 100 as described above. Exemplary values of such transit time are from values of about 2.8 ps for a multiplication gain of 1, to about 10 ps for a multiplication gain of 10. In addition, the insertion of a collector layer contributes to reducing device capacitance and thus to reducing the associated low-pass filter limitation therefore contributing to improve the overall device bandwidth at low gains and gain-bandwidth product.

[0040] The APD obtained according to embodiments of the invention may be laterally illuminated or surface illuminated.

[0041] It is to be noted that the order of the steps of the method of the invention as described and recited in the corresponding claims is not limited to the order as presented and described and may vary without departing from the scope of the invention.

Claims

1. An avalanche photodiode comprising a p-doped absorption layer, an unintentionally doped avalanche multiplication layer and an n-doped collector layer, the collector layer being capable of collecting electrons injected from the avalanche layer.

2. The avalanche photodiode of claim 1, further comprising a built-in filed layer of n+ doped material provided between the avalanche multiplication layer and the collection layer.

3. The avalanche photodiode of claim 1 or claim 2 wherein the p-doped absorption layer is doped at about $5x10^{17}$ cm^{-3} or comprises a gradual p-doping level which varies between $5x10^{17}$ cm^{-3} and $2x10^{18}$ cm^{-3}.

4. The avalanche photodiode according to any one of claims 1 to 3 wherein the p-doped absorption layer is of InGaAs material or GaAsSb material.

5. The avalanche photodiode according to any one of claims 1 to 4 wherein the collector layer is of GaInAsP material.

6. The avalanche photodiode according to any one of claims 2 to 5 wherein the built-in field layer is of InAlAs material.

7. A method of manufacturing an avalanche photodiode comprising the steps of:

   - generating a p-doped absorption layer,
   - generating an unintentionally doped avalanche multiplication layer; and
   - generating an n-doped collector layer, the collector layer being capable of collecting electrons injected from the avalanche layer.

8. The method of claim 7 further comprising the step of generating a built-in filed layer of n+ doped material between the avalanche multiplication layer and the collection layer.

9. The method of claim 7 or claim 8 further comprising the step of generating a p-doped absorption layer comprises a doping of said absorption layer at about $5x10^{17}$ cm^{-3} or comprises a gradual p-doping level which varies between $5x10^{17}$ cm^{-3} and $2x10^{18}$ cm^{-3}.

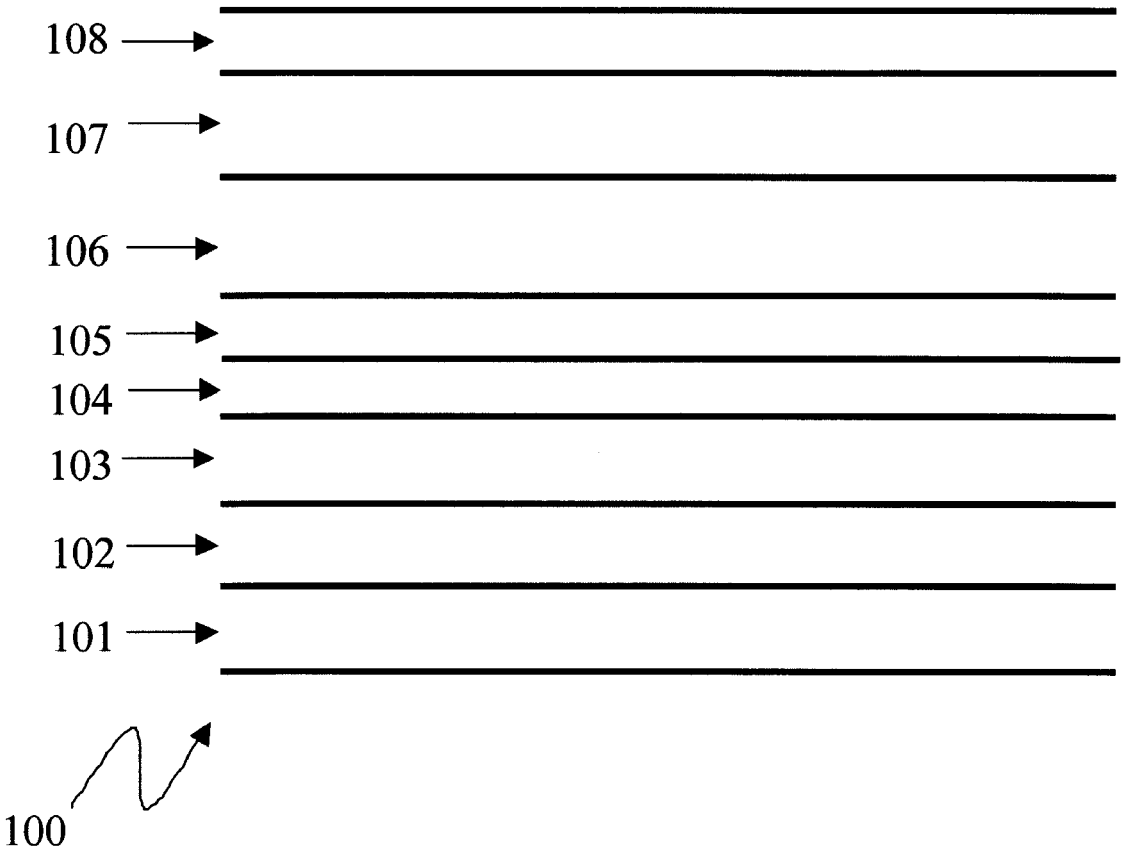


Figure 1

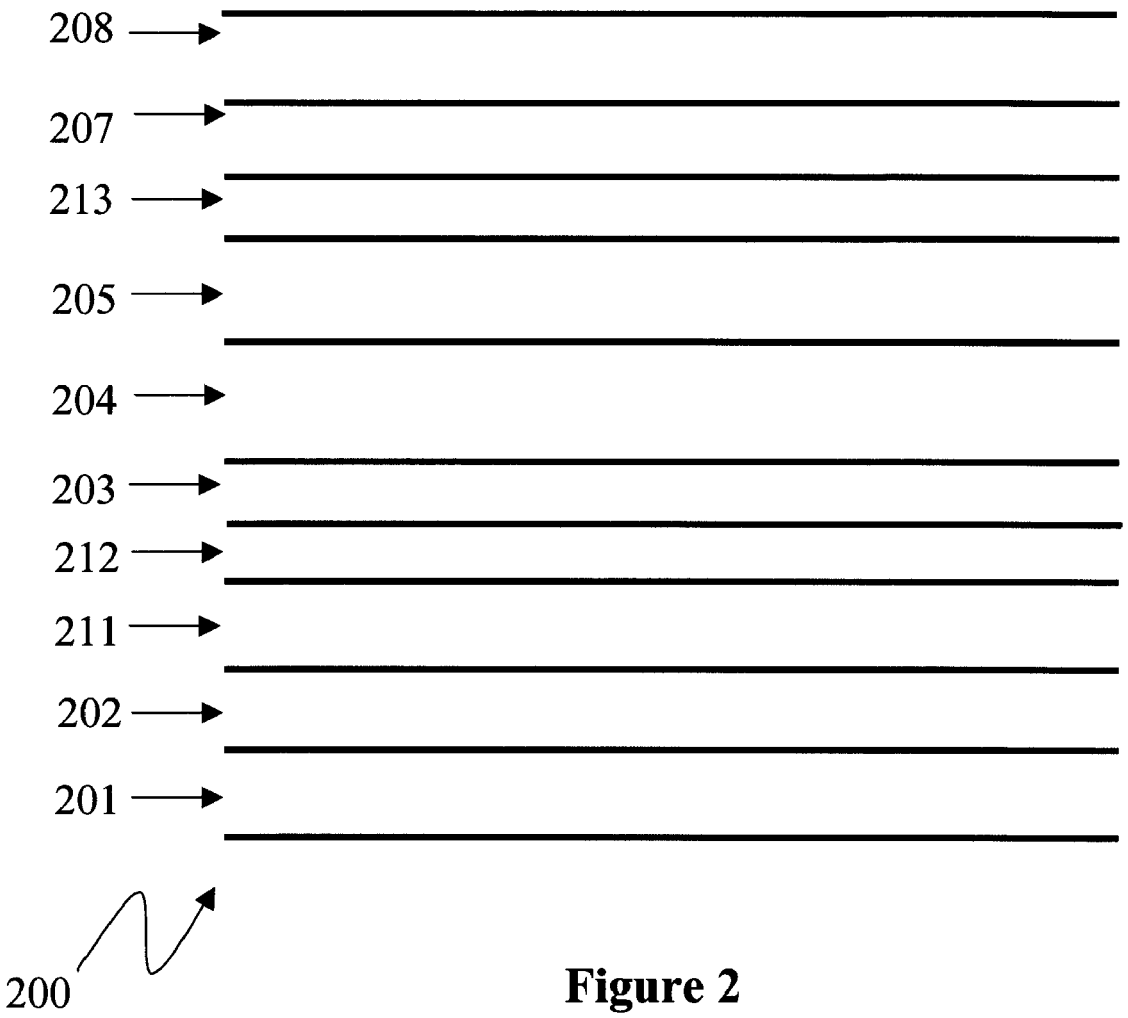


Figure 2

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 08 30 5969

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 5 369 292 A (YOO JI-BEOM [KR] ET AL) 29 November 1994 (1994-11-29) * column 4 * * abstract; figure 2 *	1-9	INV. H01L31/107 ADD. H01L31/0304
X A	US 5 654 578 A (WATANABE ISAO [JP]) 5 August 1997 (1997-08-05) * abstract; figure 2 * * column 7 *	1-5,7-9 6	
A	US 5 539 221 A (TSUJI MASAYOSHI [JP] ET AL) 23 July 1996 (1996-07-23) * abstract; figure 3 *	1-9	
A	KIM GYUNGOCK ET AL: "Enhanced frequency response associated with negative photoconductance in an InGaAs/InAlAs avalanche photodetector" APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 83, no. 6, 11 August 2003 (2003-08-11), pages 1249-1251, XP012035775 ISSN: 0003-6951	1-9	TECHNICAL FIELDS SEARCHED (IPC) H01L
A	TSUJI M ET AL: "INALGAAS STAIRCASE AVALANCHE PHOTODIODES GROWN BY METAL-ORGANIC VAPOR PHASE EPITAXY" PROCEEDINGS OF THE EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION (ECOC) MONTREUX, SEPT. 12 - 16, 1993. REGULAR PAPERS; [PROCEEDINGS OF THE EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION (ECOC)], ZURICH, SEV, CH, vol. 2, 12 September 1993 (1993-09-12), pages 389-392, XP000492244	1-9	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	16 June 2009	Heising, Stephan

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 08 30 5969

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

16-06-2009

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5369292 A	29-11-1994	JP 2695112 B2	24-12-1997
		JP 6244451 A	02-09-1994
US 5654578 A	05-08-1997	JP 2601231 B2	16-04-1997
		JP 8181349 A	12-07-1996
US 5539221 A	23-07-1996	JP 2845081 B2	13-01-1999
		JP 6291359 A	18-10-1994

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82